CHAPTER 2

INTRODUCTION TO SEISMIC DESIGN

2-1. Introduction. This chapter provides an introduction to the basic concepts of designing buildings to resist inertia forces and related effects caused by earthquakes.

2-2. General. An earthquake causes vibratory ground motions at the base of a structure, and the structure actively responds to these motions. For the structure responding to a moving base there is an equivalent system: the base is fixed and the structure is acted upon by forces (called inertia forces) that cause the same distortions that occur in the moving-base system. In design it is customary to visualize the structure as a fixed-base system acted upon by inertia forces. Seismic design involves two distinct steps—determining (or estimating) the forces that will act on the structure, and designing the structure so as to both resist these forces and keep deflections within prescribed limits.

a. Determination of forces. There are two general approaches to determining seismic forces—an equivalent static force procedure, and a dynamic lateral force procedure. This manual illustrates the equivalent static force procedure.

b. Design of the structure. The structural designer must visualize the response of the structure to earthquake ground motions and provide a design that will accommodate the distortions and stresses that will occur in the building. In certain cases, some elements cannot accommodate these stresses and distortions. Examples may include rigid stairs, rigid partitions, and irregular wings of buildings. These elements should be isolated if necessary in order to reduce damage to themselves or to reduce the detrimental effects they have on the lateral force resisting system. The development of an adequate earthquake resistant design for a structure entails the following five procedures:

(1) Selection of a workable overall structural concept.

(2) Establishment of member sizes.

(3) Structural analysis of the members to verify that stress and displacement requirements are satisfied.

(4) Adjustment of member sizes based on allowable stresses and displacements. If significant member size changes are made, it will be necessary to reanalyze the structural system to verify stress and displacement requirements.

(5) Provision of structural and nonstructural details so that the building can perform as intended.

2-3. Ground motion. The response of a given building depends on the characteristics of the ground motion; therefore it would be highly desirable to have a quantitative description of the ground motion that might occur at the site of the building during a major earthquake. Unfortunately, there is no one description that fits all the ground motions that might occur at any particular site. The characteristics of the ground motion are dependent on the magnitude of the earthquake (i.e., the energy released), the distance from the source of the earthquake (depth as well as horizontal distance), the distance from the surface faulting (this may or may not be the same as the horizontal distance from the source), the nature of the geological formations between the source of the earthquake and the building, and the nature of the soil in the vicinity of the building site (e.g., hard rock or alluvium). Although fully accurate prediction of ground motion is not possible, the art of ground motion prediction has progressed in recent years to the point that design criteria have been established in areas where historical earthquake records and geological information are available. For more information on ground motion, refer to TM 5-809-10-1/NAVFAC P-355.1/AFM 88-3, Chap 13, Sec A.

2-4. Structural response. If the base of a structure is suddenly moved, as in the case of seismic ground motion, the upper part of the structure will not respond instantaneously but will lag because of inertial resistance. The amount of lag depends primarily on the flexibility of the structure. This concept is illustrated in figure 2-1 which shows the motion in one plane. The stresses and distortions in the building will be the same as if the base of the structure were to remain stationary while time-varying horizontal forces were applied to the upper part of the building. These forces are equal to the product of the mass of the structure and the acceleration, or F = ma. (Mass is equal to weight divided by the acceleration of gravity.) Because the ground motion at a point on the earth's surface is three-dimensional (one vertical and two horizontal components), the structures affected will deform in a three-dimensional manner. Generally, however, the inertia forces generated by the horizontal components of ground motion require the greater consideration for seismic design; adequate resistance to the vertical components is usually provided by the member capacities required for gravity load design. For ordinary structures within the scope of this manual, the inertia forces are represented by equivalent static forces. However, buildings can be idealized by the use of simplified models that represent the dynamic characteristics of the structure. For special structures the idealized models are subjected to time history, response spectrum, or other dynamic analyses, and the results are used to determine the forces in the building. For more information on dynamic analysis procedures, refer to TM 5-809-10-1/NAVFAC P-355.1/AFM 88-3, Chap 13, Sec A.

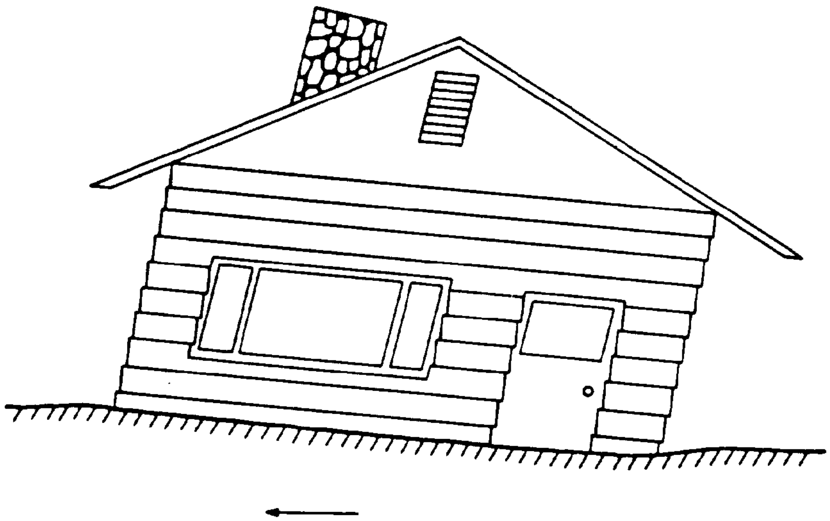
2-5. Behavior of buildings. Buildings are composed of horizontal and vertical structural elements that resist lateral forces. The horizontal elements, diaphragms, and horizontal bracing are used to distribute the lateral forces to vertical elements. The vertical elements that are used to transfer lateral forces to the ground are shear walls, braced frames, and moment resisting frames.

a. Demands of earthquake motion. The loads or forces that a structure sustains during an earthquake result directly from the distortions induced in the structure by the motion of the ground on which it rests. Ground motion is characterized by displacements, velocities, and accelerations that are erractic in direction, magnitude, duration, and sequence. Earthquake loads are inertia forces related to the mass, stiffness, and energy-absorbing (e.g., damping and ductility) characteristics of the structure. During the life of a structure located in a seismically active zone, it is generally expected that the structure will be subjected to many small earthquakes, some moderate earthquakes, one or more large earthquakes, and possibly a very severe earthquake. In general, it is uneconomical or impractical to design buildings to resist the forces resulting from the very severe or maximum credible earthquake within the elastic range of stress; instead, the building is designed to resist lower levels of force, using ductile systems. When the earthquake motion is large to severe, the structure is expected to yield in some of its elements. The energy-absorbing capacity (ductility) of the yielding structure will limit the degree of life-threatening damage: buildings that are properly designed and detailed can survive earthquake forces substantially greater than the design forces associated with allowable stresses in the elastic range. Seismic design concepts must consider building proportions and details for their ductility and for their reserve energy-absorbing capacity for surviving the inelastic deformations that would result from the maximum expected earthquake. Special attention must be given to the connections that hold together the elements of the lateral force resisting system.

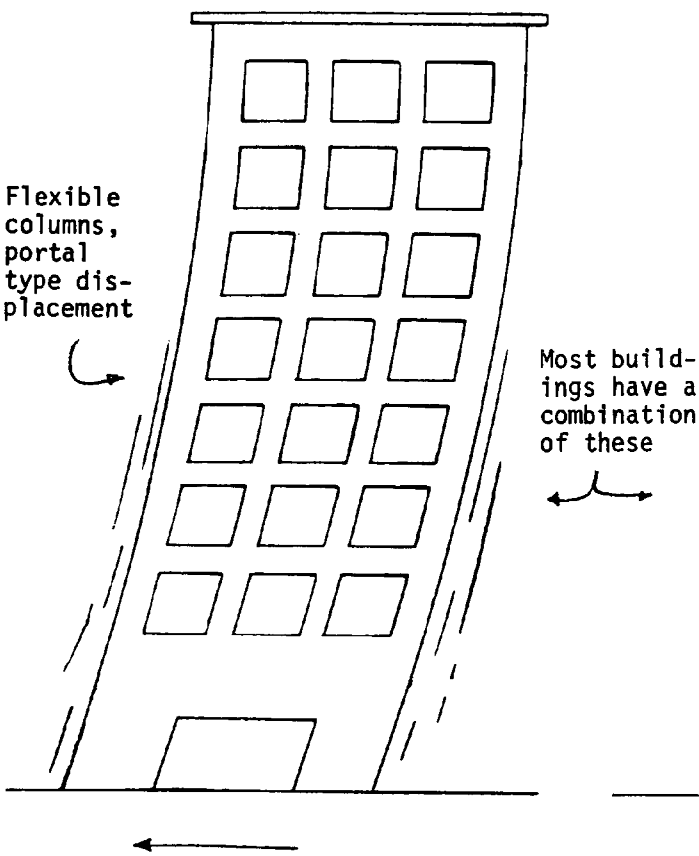
b. Response of buildings. For dynamic analysis of the response of a building to ground motion, the structural properties of the building are represented by a mathematical model that consists of an assembly of masses interconnected by springs and dampers. At each floor, tributary masses are lumped into a single mass. The force-deformation characteristics of the lateral force resisting walls or frames between floor levels are transformed into equivalent story stiffnesses. An appropriate degree of damping is assumed. Because of the complexity of the calculations for dynamic analysis methods, the use of a computer program is generally necessary; these complex methods of analysis are generally used for essential structures. Most buildings, however, are designed by the equivalent static force procedure prescribed in this manual. For buildings that require a dynamic analysis approach, refer to TM 5-809-10-1/NAVFAC P-355.1/AFM 88-3, Chap 13, Sec A.

c. Response of elements attached to the building. Elements attached to the floors of the building (e.g., mechanical equipment, ornamentation, piping, nonstructural partitions) respond to floor motion in much the same manner that the building responds to ground motion. However, the floor motion may vary substantially from the ground motion. The high-frequency components of the ground motion tend to be filtered out at the higher levels in the building, while the components of ground motion that correspond to the natural periods of vibration of the building tend to be magnified. If the elements are rigid and are rigidly attached to the structure, the forces on the elements will be in the same proportion to the mass as the forces on the structure, or F = ma (i.e., the accelerations of the elements will be about the same as the acceleration of the floor on which they are supported). However, elements that are flexible and have periods of vibration close to any of the predominant modes of the building vibration will experience forces substantially greater than the forces on the structure (i.e., accelerations of elements will be greater than floor accelerations).

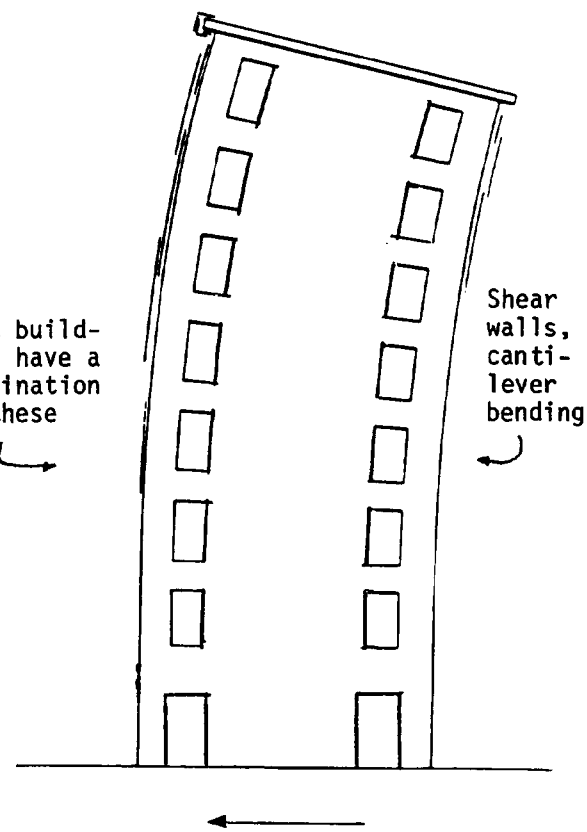
2-6. Nature of seismic codes. Codes and criteria are established from limited testing, design experience, and the observed performance of buildings in past earthquakes. A code represents the consensus of a committe: the generalized statements arrived at by compromise to cover uncertainties and



(a) *Schematic of Low-Rise Building Instantaneous Distortion During Ground Motion*



(b) *Schematic Showing Shear-Type Distortion*



(c) *Schematic Showing Bending-Type Distortion*

Figure 2-1. Schematic showing building distortions.

limitations. Codes must of necessity be short and relatively simple; therefore they do not account for all aspects of the complex phenomena of the response of actual structures to actual earthquakes. Seismic codes provide a set of design forces to represent the dynamic response of a structure subject to a complex earthquake ground motion.

a. Purpose. The basic purpose of a building code is to provide for public safety. The seismic provisions of this manual (chap 3) are based on the requirements portion of the 1990 edition of the *Recommended Lateral Force Requirements and Commentary* of the Structural Engineers Association of California. Excerpts from the commentary portion of that publication are reprinted below:[1]

(1) The primary function of these Recommendations is to provide minimum standards for use in building design regulation to maintain public safety in the extreme earthquakes which may occur at the building's site. These Recommendations primarily are intended to safeguard against major failures and loss of life, not to limit damage, maintain functions, or provide for easy repair. It is emphasized that the purpose of these recommended design procedures is to provide buildings that are *expected* to meet this life safety objective.

(2) The specified design forces given herein are based on the assumption that a significant amount of inelastic behavior may take place in the structure due to a major level of earthquake ground motion. As a result, these design forces and the related elastic deformations are much lower than those that would occur if the structure were to remain elastic. For a given structural system, the design provisions are intended to provide for the necessary inelastic behavior, and representations of the element force levels and deformations in the fully responding inelastic structure are given as appropriate multiples of the values found by the linear elastic analysis of the structure under the specified design forces.

(3) Structures designed in conformance with these Recommendations should, in general, be able to:

(a) Resist a minor level of earthquake ground motion without damage;

(b) Resist a moderate level of earthquake ground motion without structural damage, but possibly experience some nonstructural damage;

(c) Resist a major level of earthquake ground motion having an intensity equal to the strongest either experienced or forecast for the building site, without collapse, but possibly with some structural as well as nonstructural damage.

(4) It is expected that structural damage, even in a major earthquake, will be limited to a repairable level for structures that meet these provisions. The level of damage depends upon a number of factors, including the configuration, type of lateral force resisting system, materials selected for the structure, and care taken in construction.

(5) Conformance to these Recommendations does not constitute any kind of guarantee or assurance that significant structural damage will not occur in the event of a maximum level of earthquake ground motion. In order to fulfill the life safety objective of these Recommendations, there are requirements that provide for structural stability in the event of extreme structural deformations; provisions protect the vertical load carrying system from fracture or buckling at these extreme states. While damage to the primary structural system may be either negligible or significant, repairable or virtually irreparable, it is reasonable to expect that a well-planned and constructed structure will not collapse in a major earthquake. The protection of life is reasonably provided, but not with complete assurance.

(6) Conformance to these Recommendations will not limit or prevent damage due to earth movements including earth slides such as those that occurred in Anchorage, Alaska, or due to soil liquefaction such as occurred in Nigata, Japan. These Recommendations are intended to provide the minimum required resistance to earthquake ground shaking.

b. Design provisions. The seismic design provisions furnish a method for establishing the forces, describe acceptable structural systems, set limits on deformation, and specify the allowable stresses and/or strengths of the materials. The seismic design provisions are minimum requirements, and emphasis must be placed on structural concepts and detailing techniques as well as on stress calculations. The provisions are not all-inclusive: they work best for regular, symmetrical buildings. Unusual or large buildings require alternatives to the static provisions that rely on dynamic analyses and/or greater application of engineering judgment and experience in seismic design. Guidelines are given in this manual for determining when alternative procedures are required. TM 5-809-10-1/NAVFAC P-355.1/AFM 88-3, Chap 13, Sec A provides alternative procedures.

2-7. Fundamentals of seismic design. The type of structural system used will determine the magnitude of the design lateral forces. The decision as to the type of structural system to be used will be based on the merits and relative costs for the individual building being designed. There are innovative systems available for particular structural configurations and conditions, such as eccentric braced frames, seismic isolation, friction devices, and other response control systems. These systems are described below.

a. Lateral force resisting systems. Over a dozen approved lateral force resisting systems are described in chapter 3. All of the systems rely basically on moment resisting frames within a complete, three-dimensional space frame, a coordinated system of shear walls or braced frames with horizontal diaphragms, or a combination of these two systems. The vertical elements of the lateral force resisting systems are illustrated in figure2-2.

(1) In buildings where a moment resisting frame resists the earthquake forces, the columns and beams act in bending (a of fig 2-2). During a large earthquake, story-to-story deformation (story drift) may be a matter of inches without causing failure of columns or beams. However, the drift may be sufficient to damage elements that are rigidly tied to the structural system, such as brittle partitions, stairways, plumbing, exterior walls, and other elements that extend between floors. For this reason buildings can have substantial interior and exterior nonstructural damage, possibly approaching 50 percent of the total building value, and still be considered structurally safe. Moment frames are desirable architecturally because they are relatively unobtrusive compared with shear walls or braced frames, but they may be a poor economic risk unless special damage control measures are taken.

(2) Buildings with shear walls *(b* of fig 2-2) are usually rigid compared with buildings with moment resisting frames. With low design stress limits in shear walls, deformation due to shear forces (for low buildings) is negligible. Shear wall construction is an excellent method of bracing buildings to limit damage to nonstructural components, but architectural considerations may limit its applicability. Shear walls are usually of reinforced unit masonry or reinforced concrete but may be of wood in wood-frame buildings up to and including three stories. Shear wall design is relatively simple except when the height-to-width ratio of a wall becomes large. Then overturning may be a problem, and if the foundation soil is relatively soft, the entire shear wall may rotate, causing localized damage around the wall. Another difficult case is the shear wall with openings such that it may respond more like a frame than a wall.

(3) Braced frames (*c* of fig 2-2) generally have the stiffness associated with shear walls, but are somewhat less restrictive architecturally. It is usually difficult to find room for doorways within a frame; however, braces may be less obtrusive than solid walls. The concern for overturning, mentioned above for shear walls, applies also to braced frames.

(4) Structural systems may be used in various combinations. There may be different systems in the two directions, or systems may be combined in any one direction, or may be combined vertically.

(5) A building is not merely a summation of parts (walls, columns, trusses, and similar components) but is a completely integrated system or unit that has its own properties with respect to lateral force response. The designer must trace the forces through the structure into the ground and make sure that every connection along the path of stress is adequate to maintain the integrity of the system. It is necessary to visualize the response of the complete structure and to keep in mind that the real forces involved are not static but dynamic, are usually erractically cyclic and repetitive, may be significantly larger than the design forces, and can cause deformations well beyond those determined from the design forces.

b. Configuration. A great deal of a building's resistance to lateral forces is determined by its plan layout. The objective in this regard is symmetry about both axes, not only of the building itself but of its lateral force resisting elements and of the arrangement of wall openings, columns, shear walls, and so on. It is most desirable to consider the effects of lateral forces on the structural system from the start of the layout, since this may save considerable time and money without detracting significantly from the usefulness or appearance of the building. Experience has shown that buildings that are asymmetrical in plan have greater susceptibility to earthquake damage than symmetrical structures. The effect of asymmetry is to induce torsional oscillations of the structure and stress concentrations at re-entrant corners. Asymmetry in plan can be eliminated or improved by separating L-, T-, and U-shaped buildings into distinct units by use of seismic joints at the junctions of the individual wings. It should be noted, however, that this causes two new problems: providing floor joints that are capable of bridging gaps large enough to preclude adjacent structures from pounding each other, and providing wall and roof joints that are capable of keeping out the weather. Asymmetry caused by the eccentric

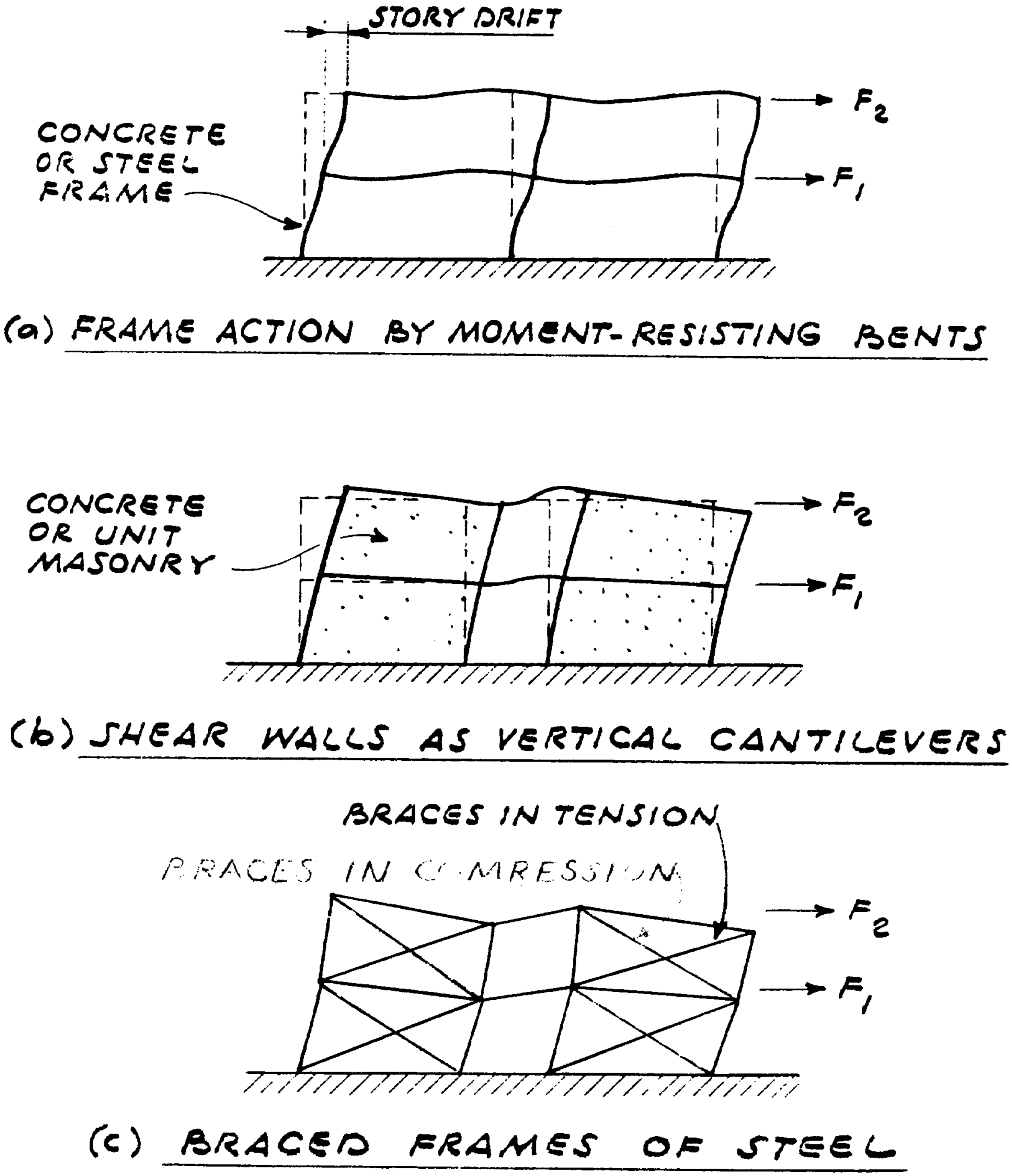


Figure 2-2. Vertical elements of the lateral force resisting systems.

location of lateral force resisting structural elements—such as in the case of a building that has a flexible front because of large openings and an essentially stiff (solid) rear wall—can usually be avoided by better conceptual planning. For example, modify the stiffness of the rear wall or add rigid structural partitions to make the center of rigidity of the lateral force resisting elements close to the center of mass. When a building has irregular features, such as asymmetry in plan or vertical discontinuity, the assumptions used in developing seismic criteria for buildings with regular features may not apply. For example, planners often omit partitions and exterior walls in the first story of a building to permit an open ground floor; in this case the columns at the ground level are the only elements available to resist lateral forces, and there is an abrupt change in the rigidity of the vertical elements of the lateral force resisting system at that level. This condition, generally referred to as a soft story, is undesirable. It is advisable to carry all shear walls down to the foundation. It is best to avoid creating buildings with irregular features; however, when irregular features are unavoidable, special design considerations are required to account for the unusual dynamic characteristics and the load transfer and stress concentrations that occur at abrupt changes in structural resistance.

c. Ductility. For practical design purposes, ductility is defined as the capacity of building materials, systems, or structures to absorb energy by deforming in the inelastic range. Ductility allows structures to withstand large earthquake forces when they have been designed economically on an elastic basis to lower, code-level forces. Structural steel is a ductile material, but when steel members are joined to make a lateral force resisting frame, special details are needed in order to ensure ductile behavior of the assembly. Brittle materials such as concrete and unit masonry can be reinforced with steel to provide strength, but they need additional details to achieve the ductility characteristics necessary to resist large seismic forces. In concrete columns, for example, the combined effect of flexure (due to frame action) and compression (due to the action of the overturning moment of the structure as a whole) produces a common mode of failure: buckling of the vertical steel and spalling of the concrete cover near the floor levels. In columns with proper spiral reinforcing or closely spaced hoops, the reinforcing has a confining effect that produces greater reserve strength and ductility.

d. Redundancy. Redundancy is a highly desirable characteristic for earthquake resistant design. When the primary element or system yields or fails, the lateral force can be redistributed to secondary elements or systems to prevent progressive failure.

e. Connectivity. It is essential to tie the various structural elements together so that they act as a unit. The connections between the elements are at least as important as the elements themselves. Prevention of collapse during a severe earthquake depends upon the inelastic energy absorbing capacity of the structure, and this capacity should be governed by the elements rather than by their connections; in other words, connections should not be the weak link in the structure. As a general guide, if no other requirements are specified, connections should be adequate to develop the useful strength of the structural elements connected, regardless of the calculated stress due to the prescribed seismic forces.

f. Nonstructural participation. For both analysis and detailing, the effects of nonstructural partitions, filler walls, and stairs must be considered. The nonstructural elements that are rigidly tied to the structural system can have a substantial influence on the magnitude and distribution of earthquake forces. Such elements act somewhat like shear walls, stiffening the building and causing a reduction in the natural period and an increase in the lateral forces and overturning moments. Any element that is not strong enough to resist the forces that it attracts will be damaged; it should be isolated from the lateral force resisting system.

g. Damage control features. The design of a structure in accordance with the seismic provisions of this manual will not fully ensure against earthquake damage because the horizontal deformations from design forces are lower than those that can be expected during a major earthquake. However, without increasing construction costs, a number of things can be done to limit earthquake damage that would be expensive to repair. In considering a building's response to earthquake motions, it is important to keep in mind the structural system and the geometry of the building. It should be assumed that deformation (story drift) during a major earthquake may be several times that resulting from the design lateral forces. A list of features to minimize damage follows:

(1) Details that allow structural movement without damage to nonstructural elements can be provided. Damage to such items as piping, glass, plaster, veneer, and partitions may constitute a major financial loss. To minimize this type of damage, special care in detailing, either to isolate these elements or to accommodate the movement, is required.

(2) Glass windows should be isolated with adequate clearance and flexible mountings at edges to allow for frame distortions.

(3) Rigid nonstructural partitions should have room to move at the top and sides.

(4) In piping installations, the expansion loops and flexible joints used to accommodate temperature movement are often adaptable to accommodating seismic deflections.

(5) Freestanding shelving can be fastened to walls to prevent toppling. Shelves can be provided with lips or edge restraints to prevent contents from falling off in an earthquake.

2-8. Alternatives to the prescribed provisions. Alternatives to the seismic provisions of this manual are permitted if they can be properly substantiated. The most common alternative is dynamic analysis. Dynamic analysis may be required for such cases as irregular buildings and buildings with setbacks. The provisions herein will indicate when dynamic analysis is required. Dynamic analysis may be used as an option for such cases as making a more efficient design or designing to a particular earthquake ground motion. In any case, using dynamic loading and computer analysis, one can more accurately predict how a proposed building will act and deform under ground motions from a specific earthquake. The resulting deformations may sometimes cause joint rotations and stresses quite different from those determined from the prescribed static loadings. Before proceeding with the equivalent static force procedure, the designer should make sure that there are no special conditions that would warrant or require the use of more rigorous methods.

a. Elastic dynamic analysis. For most buildings requiring an alternative design method, an elastic dynamic analysis procedure is sufficient to determine load distribution and member forces for design earthquake motion. A response spectrum analysis with the modes combined by the square-root-of-the-sum-of-the-squares (SRSS) method or by some other approved method is generally sufficient for an elastic analysis. A time history analysis may be used if necessary.

b. Inelastic dynamic analysis. For major buildings, for which added assurance is required that the building can withstand a major earthquake without collapse or within a limited range of damage, an inelastic dynamic analysis may be used. This usually is a time history analysis; however, other approximate procedures that can estimate inelastic effects may be used.

c. Seismic design guidelines for essential buildings. When authorized by the approval agency, TM 5-809-10-1/NAVFAC P-355.1/AFM 88-3, Chap 13, Sec A will be used as a supplement to this manual for dynamic analysis procedures.

d. Innovative systems. There are new systems and devices for controlling and/or limiting the response of structures to earthquake ground motion. The best known of these systems are seismic isolation systems (sometimes called base isolation systems). Seismic isolation is based on the premise that the structure can be substantially decoupled from potentially damaging earthquake motions. By decoupling the structure from the ground motion, seismic isolation reduces the level of response in the structure from the level that would otherwise occur in a conventional fixed-base building, or conversely, offers the advantage of designing with a reduced level of earthquake load to achieve the same degree of seismic protection and reliability as a conventional fixed-base building. Tentative provisions for seismic isolation are given in the SEAOC Commentary, Appendix 1L. The subject is not covered in this manual because it requires the knowledge of specialists. Provisions for other innovative systems such as damping devices are not covered in this manual; they are in various stages of development, ragning from concept to implementation.

2-9. Future expansion. When future expansion of a building is contemplated, it is generally better to plan for horizontal expansions rather than for vertical growth because there will be greater freedom in planning the future increment, there will be less interruption of existing operations when additions are made, and the first increment will not have to bear a large share of the cost of the second increment. For future vertical expansion, the foundation, floor/roof system, and structural frame must be proportioned for both the initial and the future design loadings, including the seismic forces. For future horizontal expansion, either a complete structural separation between the two phases must be provided, or the first increment must be designed for its share of the loads under both conditions: the first increment and the expansion. Many buildings that have been designed for expansion under past seismic criteria do not satisfy the present criteria; if these buildings are to be expanded in the future, they will have to be evaluated to determine if upgrading is necessary. High cost may be incurred if seismic strengthening is required, especially in high seismic zones.

2-10. Existing buildings. Existing buildings may be upgraded, altered, or enlarged.

a. Upgrades. The upgrading of existing buildings is covered in TM 5-809-10-2/NAVFAC P-355.2/AFM 88-3, Chap 13, Sec B.

b. Alterations. When a building is altered, it will be subject to upgrading if the alteration would reduce the vertical and/or lateral load carrying system capacity or if an alteration in function puts the building in an essential or hazardous occupancy category.

c. Additions. Vertical and horizontal extensions can have a drastic effect on the performance of the building. Therefore, additions should be kept structurally separate from the existing building whenever possible. When the addition is not separated and a significant change occurs in the total weight, in the weight distribution, or in the building lateral force resisting system's rotational or translational stiffness, an upgrade will be done.

2-11. Major checkpoints. The process of achieving an adequate building must start with conceptual planning and be carried through all phases of the design and construction program. The major check points include site investigation; coordination of the work of the architect and engineers (structural, mechanical, and electrical), to establish the plan, the system, and the materials of construction; establishment of design criteria for the specific facility; identification and location of primary structural elements; determination and distribution of lateral seismic forces; preparation of design calculations; detailing of connections; detailing of nonstructural parts for damage control; preparation of clear, complete contract drawings and specifications; checking of shop drawings; quality control inspection; and surveillance over any change in conditions during the entire construction period.